International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:9, No:10, 2015

Grating Scale Thermal Expansion Error Compensation for Large Machine Tools Based on Multiple Temperature Detection

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***Abstract*—**To decrease the grating scale thermal expansion error, a novel method which based on multiple temperature detection is proposed. Several temperature sensors are installed on the grating scale and the temperatures of these sensors are recorded. The temperatures of every point on the grating scale are calculated by interpolating between adjacent sensors. According to the thermal expansion principle, the grating scale thermal expansion error model can be established by doing the integral for the variations of position and temperature. A novel compensation method is proposed in this paper. By applying the established error model, the grating scale thermal expansion error is decreased by 90% compared with no compensation. The residual positioning error of the grating scale is less than 15μm/10m and the accuracy of the machine tool is significant improved.

***Keywords*—**Thermal expansion error of grating scale, error compensation, machine tools, integral method.

I. Introduction

To provide industrial products with good quality and high consistency, errors in machining process should be minimized. During machining process, errors include geometric and kinematic errors, thermal errors, fixture-dependent errors, cutting force induced errors and other errors [1]. Among them, thermal error account for 40-70% of the total errors [2]. For large machine tools, the position repetitive errors and the positioning errors are decreased by configuring with grating scales rather than rotary encoders. And grating scales are made of steals or glasses generally. However, the grating scale is also affected by the inner heat source during the machining process and it will thermal expand. The expansion of the grating scale will cause a thermally induced positioning error directly. The thermal induced positioning error will be considerable if the stroke is large. And the error should be decreased.

There are two methods to minimize the thermal error: error avoidance and error compensation. Error avoidance is to minimize the error by optimizing the mechanical design. Xu [3] presented a method to place an air cooling system in a ball screw shaft to minimize the thermal errors. The positioning accuracy of the ball screw system is significant improved after using the air cooling system. In additions, using the material of non-expansion coefficient such as the glass ceramic as the grating scale is a smart choice. However, the cost is dramatic expensive. The other method is error compensation. And error compensation techniques have been considered as an effective and cost-efficient way to improve the machine accuracy [4]-[6].

Error compensation techniques aim to create an artificial error to eliminate the original error [7]. Many researchers have done many studies about error modeling and compensation in the past few decades. Fan [8] proposed a novel error modeling method based on orthogonal polynomials to enhance the accuracy of machine tools. And the thermal errors are decreased 90% after compensation. Wang [9] proposed a modeling way based on Newton interpolation method to decrease the thermally induced positioning error. Applying the novel method in a vertical machining center, the accuracy of the VMC is significant improved. However, to decrease the grating scale thermal expansion error of large machine tools is still a tough work and its compensation method needs to be further studied.

In this paper, to decrease the grating scale thermal expansion error of large machine tools, a novel modeling and compensation method is proposed. An experiment is conducted to validate the compensation effect. The result shows that the positioning accuracy of grating scale is significant improved.

II. Analysis of Thermal Expansion Error

To study the thermal expansion error of grating scales, an experiment is conducted on a commercial floor type borer TK6920. The parameters of the machine tool are shown in Table I. To simulate the actual machining moving, the worktable is reciprocated along its whole stroke of 10m at a feed rate of 5000mm/min. The positioning error is measured by the XL-80 laser measurement system from Renishaw corporation every 20min. The error data are shown in Fig. 1. After the 240min warming phase, the positioning error is increased from 50 μm to 340μm. The main factor is the thermal expansion of the grating scale. The positioning error curves sharp remain unchanged and each error curve can be obtained by rotating the 0min curve by an angle on a fixed point. Therefore, the positioning error can be separated into two parts: one is the static geometric error related to the axis position, and the other is the thermal expansion error related to the temperature and axis position.

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TABLE I
PARAMETERS OF THE FLOOR TYPE BORER

TK6920	Parameters(mm)
Stroke of X-axis	10000
Stroke of Y-axis	4000
Stroke of Z-axis	1200
Stroke of W-axis	1200
Diameter of boring axis	ϕ200

The positioning error can be expressed as:

$$\delta_p(p,T) = \delta_{pG}(p) + \delta_{pT}(T) * p \tag{1}$$

where $\delta_p(p,T)$ indicates the positioning error of the p-axis, $\delta_{pG}(p)$ indicates the geometric error, $\delta_{pT}(T) * p$ indicates the thermal expansion error.

III. THERMAL EXPANSION ERROR MODELING

The thermal expansion error is induced by the elongation of the grating scale. The elongation can be expressed as:

$$\delta_{pT}(T) * p = \Delta L = \Delta T * L * \alpha \tag{2}$$

where ΔL / μm indicates the elongation of the grating scale, ΔT / ℃ indicates the temperature variations of the grating scale, L / m indicates the length of the grating scale, $\alpha / (\frac{10^{-6}}{℃})$ indicates the linear expansion coefficient.

To study the temperature variations of the grating scale, eight temperature sensors are installed on the grating scale and the temperature data are recorded real-time. The temperature sensor is developed independently and the temperature chip Tsic506F is imported from the IST Corporation in Switzerland. The resolution of the temperature sensor is 0.06°C. What is more, the bottom material of the sensor is magnets, which can easily attach to the ferrous surface of machine tools. The installation of temperature sensors is shown in Fig. 3. And the temperature variations during the entire 240min are shown in Fig. 2.

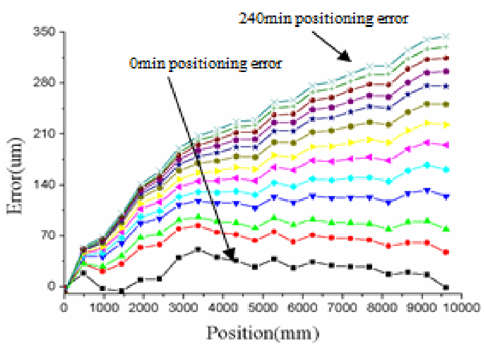

Fig. 1 Positioning errors during warming process

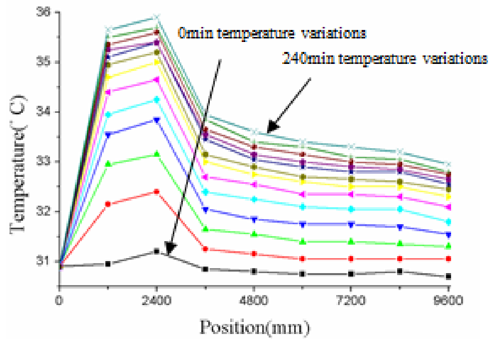

Fig. 2 Grating scale temperature variations during 240min

To match the error measuring interval of 480 mm, the temperature points of interval 480mm are calculated as:

$$T_X = \begin{cases} (\frac{T_1 - 30.9}{1200}) * X + 30.9, X \in [0,1200] \\ (\frac{T_2 - T_1}{1200}) * (X - 1200) + T_1, X \in (1200,2400] \\ (\frac{T_3 - T_2}{1200}) * (X - 2400) + T_2, X \in (2400,3600] \\ (\frac{T_4 - T_3}{1200}) * (X - 3600) + T_3, X \in (3600,4800] \\ (\frac{T_5 - T_4}{1200}) * (X - 4800) + T_4, X \in (4800,6000] \\ (\frac{T_6 - T_5}{1200}) * (X - 6000) + T_5, X \in (6000,7200] \\ (\frac{T_7 - T_6}{1200}) * (X - 7200) + T_1, X \in (7200,8400] \\ (\frac{T_8 - T_7}{1200}) * (X - 8400) + T_1, X \in (8400,9600] \end{cases} \tag{3}$$

where $T_1,T_2,T_3,T_4,T_5,T_6,T_7,T_8$ indicates the read temperature data by the 8 temperature sensors, separated. X / mm indicates the position where the calculated temperature represented.

By applying (3), the temperature variations of every point on the grating scale during the entire 240min can be calculated. And the temperature variations of interval 480mm are shown in Fig. 4.

The temperature rising values during the 240min relative to the temperature data in 0min are shown in Fig. 5. And it can be seen in Fig. 5 that the variation of each point on the grating scale is not the same. Each point should be analyzed separately. The thermal expansion error of the grating scale is calculated by doing the integral for the variations of position and temperature. Its mathematical equation is expressed as:

$$\delta_{pT}(T, p_n) = \int_0^{p_n} \Delta T_p * \alpha * dp \tag{4}$$

where $\delta_{pT}(T, p_n)$ indicates the thermal expansion error in position p_n, ΔT_p indicates the temperature variations in position p and $p \in [0, p_n]$, α=11.7 .

As for the geometric error in (1), the least square method is used to model for it. Its mathematical equation is expressed as:

$$\delta_{pG}(p) = -5.23 + 0.00311p + 5.16\times10^{-6}p^2 - 1.06\times10^{-9}p^3 + 5.27\times10^{-14}p^4 \quad (5)$$

The modeling result is shown in Fig. 6. The largest residual error is 13 µm or less. And the geometric error is decreased by 60%.

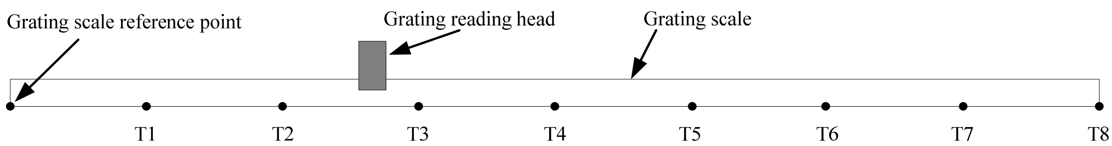

Fig. 3 The installation of temperature sensors

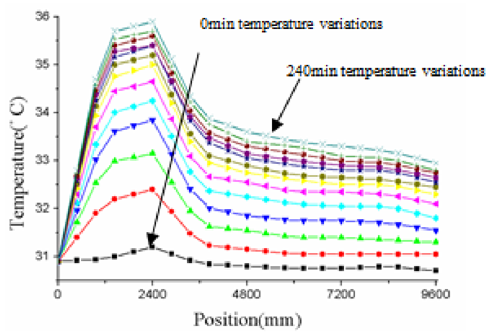

Fig. 4 Temperature variations of interval 480mmm

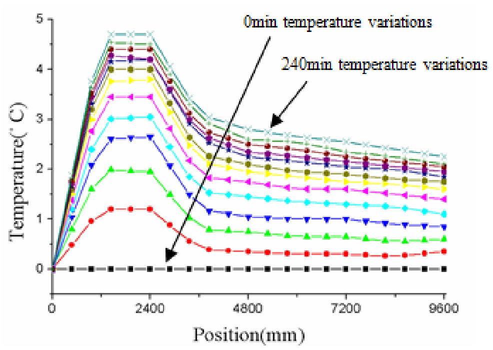

Fig. 5 Temperature rising relative to the temperature in 0min

According to (1), the synthesis positioning error of the grating scale is established. The error model curves during 240 min are shown in Fig. 7.

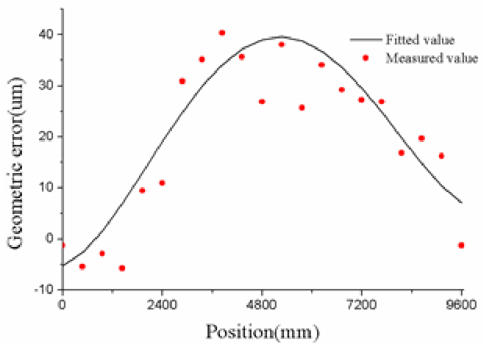

Fig. 6 Geometric error modeling results

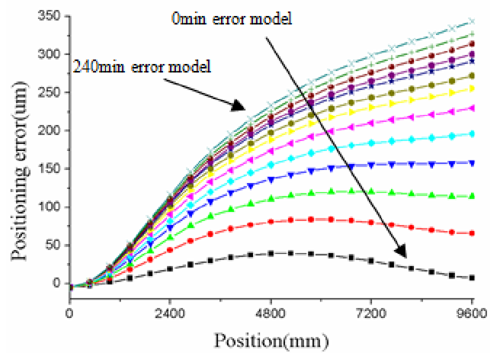

Fig. 7 Synthesis positioning error model

IV. Error Compensation

To validate the accuracy and robustness of the proposed model, an experiment is conducted on a commercial floor type borer. The worktable is reciprocated along the range of 2400-7200mm at a feed rate of 5000mm/min. The positioning errors are measured in 30min and 60min separately. The error compensation is achieved by creating a new error to eliminate the original error. An error compensation system is developed based on the function called External Mechanical Original Offset in Fanuc CNC system. The comparison of with and without compensation is shown in Fig. 8. The compensation results show that the residual positioning error is less than 15µm/10m after compensation. The accuracy of the machine tool is improved by 90% compared with no compensation.

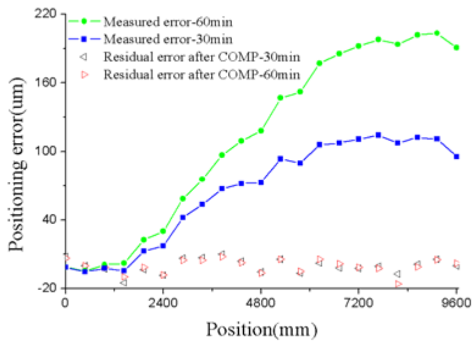

Fig. 8 Compensation results

V. Conclusions

To decrease the thermal expansion error of grating scales installed on large machine tools, a novel compensation method is proposed. The temperature variations of the grating scale are obtained by using the developed temperature sensors. The thermal expansion error model is established by doing the integral for the variations of position and temperature. Applying the error model, the positioning error of the grating scale is compensated. The positioning accuracy of the machine tool is improved by 90% compared with no compensation.

Acknowledgment

This research was sponsored by the Liaoning Province Scientific and Technical Innovation Key Special Projects [No. 201301001], the National Science Foundation Projects of PR China [Nos.51275305], the Shanghai Municipality Industry-University-Research Cooperation Projects [No.CXY-2013-29]. The Shanghai Municipality Absorption and Innovation Projects of Import Technology [No.13XI-07].

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